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Tunnel Timbering and Lining

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TUNNEL TIMBERING AND LINING

BY

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

RODNEY LINTON BELL

ENTITLED TUNNEL TIMBERING AND LINING

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

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TUNNEL TIMBERING AND LINING

INTRODUCTION

The subject will be divided into three divisions and taken up in the following order: 1st, a short history of the art of tunneling, and its developement up to modern times; 2nd, Tunnel Timbering, under which will be given the general principles of timbering, a discussion of the systems of timbering as developed by the engineers of different countries, and a few specific examples with sketches showing different methods employed in heavy soil; 3rd, The Lining of Tunnels, which involves a discussion of the relative merits of the different materials used for lining together with their costs.

A SHORT HISTORY OF THE ART OF TUNNELING

If we take the finished product as the basis of comparison, none of the tunnels excavated by the ancients would take a very high place as examples of engineering skill, but there is one thing which stands out from most of these works, and which causes even the engineers to reflect; this is the wonderful perseverance shown by the ancients in pushing their tunnels to a successful completion. When we consider that their means of excavation were limited to hand tools and wedging supplemented occasionally by the "fire setting" system of excavation, we begin to understand the enormous amount of work which it took to excavate some of these tunnels, and it would be impossible for us to imagine how the work could have been done if we did not remember that the laborers were slaves, and that the value of human life was held at naught.

The "fire setting" system consisted simply in heating the rock and suddenly cooling it with water, thus disintegrating it. Diodorus, in an account of mining operations in Ancient Egypt speaks of the "fire setting" system being employed, and gives a horrible picture of the suffering of the slaves and captives who were condemned to work in the mines. The use of fire in tunnel, of course, gave a very impure atmosphere and the only device of which we have any record as being used by the ancients to improve the ventilation consisted in waving large sheets of cloth over the shaft. These acted as fans, agitating the air,

and afforded some little relief. The "fire setting" system was not confined to the ancients, but was used in mining operations in Europe as late as the beginning of the 17th century, and we have records of its use in Japan, for driving long mining tunnels as late as the latter part of the 19th century.

In Egypt proper almost all of the tunnels excavated were used for tombs, while in Nubia the excavations were made in the form of temples. These temples date back to 1500 BC. The oldest underground temples are found in India and date back to 2000 BC. All of these temples were carved in solid rock. This is characteristic of all of these old excavations. They were through rock so that little or no knowledge of timbering was required. Plenty of slaves and time were the essential things which assured success.

Among the Medes and Assyrians tunneling was carried on at an early date. They did not build tombs on such a large scale as the Egyptians, but confined their efforts more to building tunnels for drains and water supply. At Babylon there is an arched tunnel, under the Euphrates, which connected the royal palace with a temple. This was 12 feet high and 15 feet wide and was lined with brick. This tunnel can hardly be cited as an example of subaqueous work as we are told by Herodotus that the waters of the Euphrates were diverted from their channel before the work on the tunnel began.

Elaborate arrangements were often made in ancient cities for drainage and water supply and we are told that when Caesar arrived at Alexandria, he found the city almost hollow underneath from the numerous aquaducts.

So far the biggest part of underground work has been through rock, and the excavations made were used largely for temples of worship, as tombs for the dead, rather than fulfilling any practical use. But when we came to examine the work of the Romans we find the tunneling had been brought up to a high stage of development. The remains of their great works are being discovered at the present day and in many instances are in an excellent state of preservation. The Romans built tunnels for passages, for drainage and for their aqueducts not only in Italy but wherever their conquests led them.

One of the most difficult pieces of tunnel work undertaken by the Romans was the draining of Lake Fucinus (now Celano). This tunnel was about three miles in length and had a cross section of about 19 feet high and 10 feet wide. It was completed in A.D. 52 at an enormous expense. 130,000 men were employed on it for 11 years. Something like 22 shafts were sunk on the line. The Romans generally used sloping shafts in preference to vertical ones.

A book might easily be written on the description of the Roman's aqueducts and their systems for the disposal of sewerage. Wherever the Romans went they left evidence of their skill in this line of engineering work.

After the fall of the Western Empire, we have no marked mention of any kind of tunnel work in Europe through the dark ages. The modern revival of tunnel construction received its first impulse from Anne of Lusignan, in 1450, who in that year commenced the construction of a tunnel in the Alps between Nice and Genoa. The work was finally abandoned in 1794 after about 7500 feet of

tunnel was said to have been completed.

The "fire setting" system of excavation was still in use in Europe as late as 1600 A.D., but even at this time the art of timbering had reached a high state of development. In fact, the methods then were practically the same in principle as those used now, the chief difference being in the extension of the system from mining work to cover the large tunnels driven for canals and railroads.

In the 18th century large tunnels began to be constructed for canals through solid rock, but it was not until the early part of the 19th century that the first large tunnel was driven thruogh soft ground. This tunnel was under the Thames. The English were the pioneers in this work followed by the Frech, Belgians, Germans and Austrians and we Americans have derived the main features of our system, for tunnel timbering in soft ground, from the Europeans.

The latest and greatest advancement in tunnel construction has been made possible by the introduction of high explosives and power drills.

Drinker says that in past ages the art of tunneling has gone hand in hand with the higher civilization with each era. As a people become more civilized, its civilization can be gauged by its progress in tunnel construction, and whatever be the motive the result is always the same. The religious fanaticism of the Egyptians and Hindus manifested itself in their temples and grottos. The more practical bent of the Assyrians is shown in their tunnels and archways. Beginning with the Greeks, the progress of the age is shown in their drainage tunnels, and in

the great public works of Rome, tunnel building reached its culmination in ancient times. During the dark ages we would expect to find no evidence of tunnel construction except in the crypts and cloisters of those days. Finally, with modern civilization, we have tunneling in its last and greatest developement. This is most natural, for, of all branches of construction, it is one of the most difficult. A barbarous people may, perhaps, develop a high degree of perfection in the mere art of open air building, where stone can be piled on stone in the light of day; but it takes the energy, knowledge, experience and skill of an educated and trained class of men to cope with the unknown dangers of the dark depths that are to be invaded by the tunnel-man.

TUNNEL TIMBERING.

Principle of Timbering.-

The main characteristic of tunnel timbering is strutting and bracing apart. The timberman has to guard against compression, and as all cutting and jointing of timber tends to weaken it, the aim is to dispose of the timber as far as possible in its natural state, with little or no dove-tailing or jointing. The stronger the pressure is, the less need be paid to so-joint the timber to hold them together, the pressure does that, and the greater it becomes, the tighter is the connection.

The timbering in a tunnel may be said to consist of outside lagging or poling boards, caps, rafters or bars, which directly support the lagging, and the props below, which support the caps, bars or rafters.

There are a number of general principles which apply to all systems of tunneling, and it may be well to enumerate them.

Judgement should be used in the selection of the timber. In heavy ground the hardest may not always be the best, spruce being often preferred to oak. The wood should never be weakened in heavy ground by cutting or mortising, and the pressure of the ground should be distributed, and never concentrated at any one point of the timbering. The entire system of an enlarged section should be built so that each timber will form a part of one whole. It is also necessary to have the timbers supplement each other, as well as acting together, so that the removal or breaking of any one timber will not bring down the entire structure. The timber should be disposed so that

up to the breaking point, the increase of pressure only serves to better bind the parts together. Centers of rotation should be avoided as much as possible. It is very necessary to see that the foundation timbers have a good footing in order to guard against any sinking. The whole timbering should be kept under equal strain. Hollow spaces forming outside and on one side of the sedtion, relieving the pressure on that side, while it is still heavy on the other may bring about disastrous results, if they are not broken into and filled.

It must always be remembered that timbering in most systems is only (except Block System) a means to an end. It is only erected to be taken down. The best system, therefore, is not only the one which is strong, but which affords the best facilities for rapid work, and wherein the parts can be so disposed that the transportation of material can be carried on with the least hindrance, and the arching readily erected in as clear a space as possible.

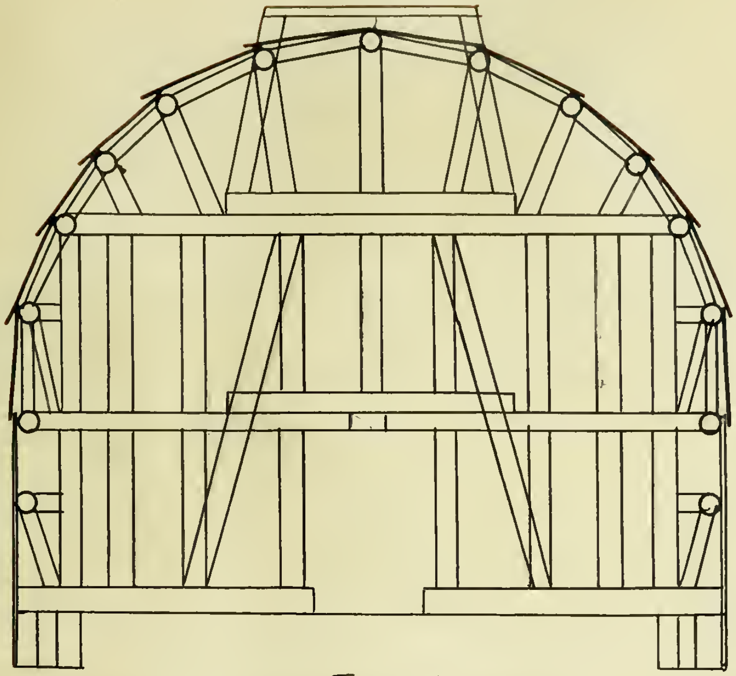

Fig 1

English System of Timbering

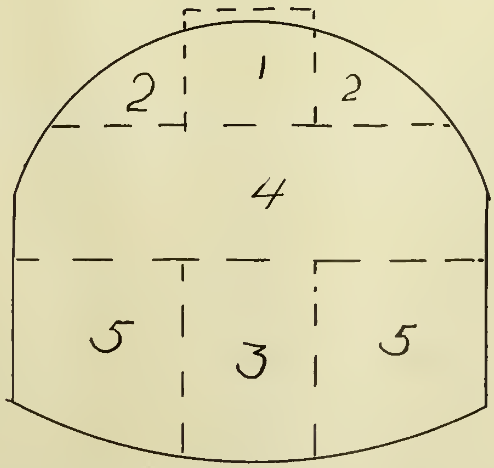

Fig 1.a

Sequence of Excavation

THE SYSTEMS OF TUNNEL TIMBERING.

The recognized systems of tunnel timbering are five in number, viz: English, Belgian, German, Austrian and American, and they will be discussed in this order.

The English system of tunnel timbering, often called the bar system, was developed during the building of the first Thames Tunnel and it has stood the test of time and is to-day (60 years later) regarded with as much favor as it ever was. The method of operation is, as follows: The preliminary top heading is taken out, and the long crown bars are inserted, which support the roof while the lower tunnel core is taken out, leaving a clear open space for the masons to run up the arching. If the work is carried on with the proper care, in ordinary soft ground, the crown bars can be pulled forward after the masonary has been completed, thus affording a considerable saving of both time and money. When the bars are pulled forward one end rests on the masonary and affords a very substantial support for the timbering. Fig. 1 gives a good idea of how a completed section of timbering by the English system appears. Fig. 1a gives diagramatically the sequence of excavation and shows how the bars are put in. As shown in this figure, the bottom heading (3) affords an excellent drainage for the entire cross section. The large open space afforded by the system enables the material to be removed quickly and economically and also is a great aid to ventilation. The masons and the miners cannot both work on the same section, but alternate working faces can generally be managed so that they can exchange places as their departments are completed. The English system does not use as much heavy timber

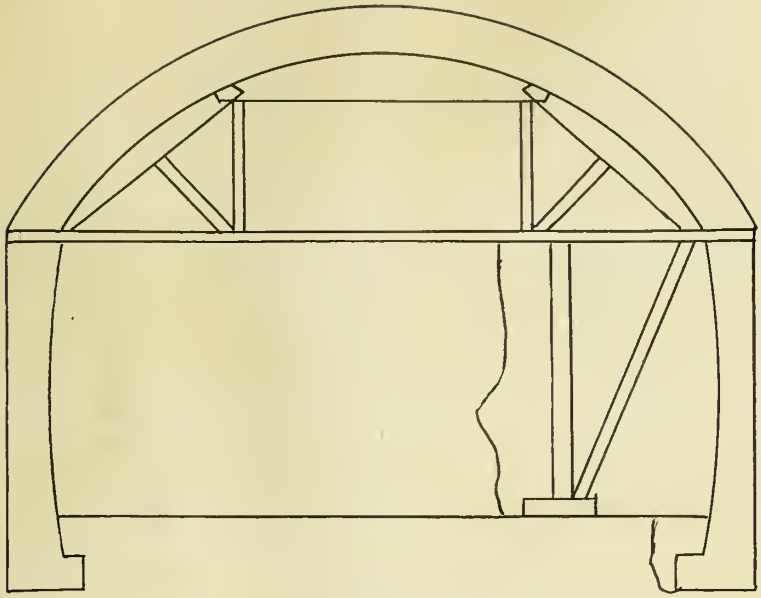

Fig 2

Belgian System of Timbering

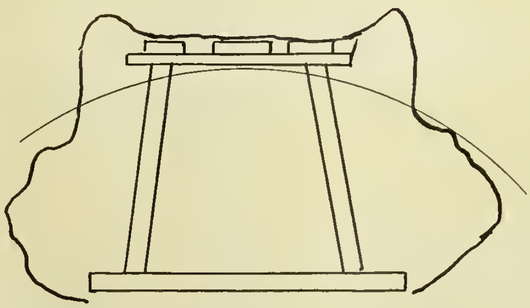

Fig 2 a

First Enlargement of Top Heading

as some of the other systems and in extremely heavy ground more must be used, but up to the breaking point this system is a beautiful example when the stronger the pressure becomes, the closer the system is bound.

The Belgian system originated with the construction of the tunnel on the canal from Charleray to Brussels in 1828. A bed of quick-sand was struck, which proved so difficult to work that after an iron shield had proven ineffective, it was decided to build the tunnel in an open cut and fill in again over the arching. The open cut was only carried down to the spring of the arch which was built and covered over with earth. The arch was then under-pinned, the bottom taken out and the side walls put in. After the quick sand had been passed the plan of building the arch first was tried in the tunnel proper and found to be entirely satisfactory. Fig. 2 shows the arch and the method of underpinning it. Sometimes a central core was left, but more generally this was not done. Fig. 2a shows the method of timbering the top heading and the first enlargement of the same. One of the things to be noticed in this system is the fact that the tendency is to concentrate the pressure, taken up by the props, at one point, which is exactly adverse to the best tunnel timbering principles. Correct timbering is applied when pressure is met and equally transmitted and distributed as far as possible through the entire system. Other disadvantages that are open to adverse criticism in this system, are that the material is not accessible in a large body at once, and the successive small extractions are consequently costly, and the custom of underpinning the arch is condemned by a large number

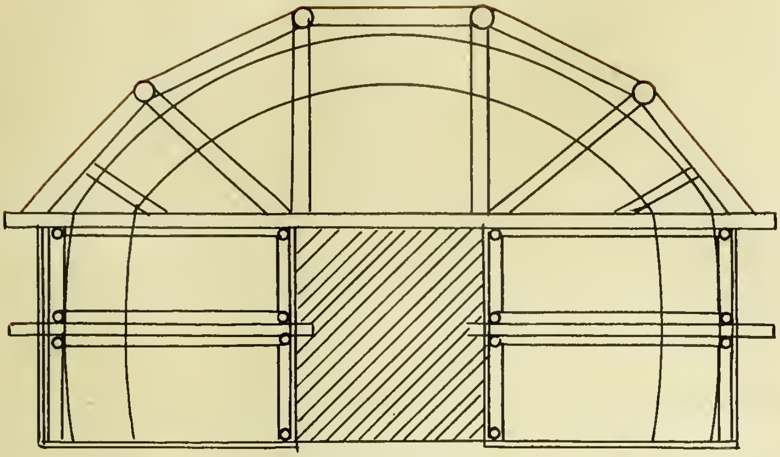

Fig 3

German System of Timbering

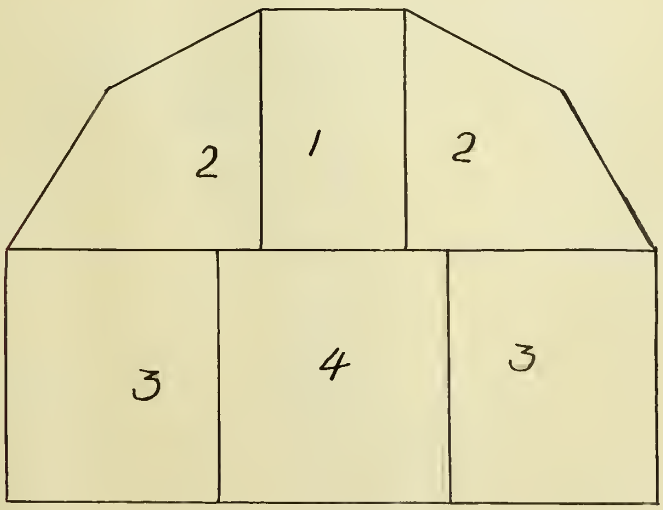

Fig 3a

Sequence of Excavation

of foreign engineers and has never met with favor in America. The question of transportation in this system offers considerable difficulty, both as to the debris, which must be taken out, and for the materials for arching which have to be brought in. One big advantage of this system is that the early securing of the roof by an arch does away with the necessity of a great deal of subsequent timbering.

The leading and the most striking characteristic of the German system is the employment of a central core to help support the arch. This system was first used in a crude way on the St. Quentin Canal in France in 1803. By origin the system is French, but the engineers of that country never seemed to care much for the system, while the Germans adopted and improved it, so that it is perfectly correct to speak of it as the German system. Fig. 3 shows a sketch of this system with the core in place, and Fig. 3a gives the sequence of operation. A top heading is first driven and timbered. This section is enlarged, continuing on down the sides to the bottom of the section. The side walls are built up from each side and the core is left in place until the masonry is complete. In hard ground the friends of this system claim that it gives cheap working as the core is readily removed, as it has four open blasting places. In soft ground it is not so good. It is true that the openings are small, but to depend upon a core of soft material to take away pressure seems to be a very poor policy. The core does save considerable timber if it is strong enough to support the weight. It is hard to see where its friends can claim cheap transportation which is carried on through the side drifts where the masonry work is being done.

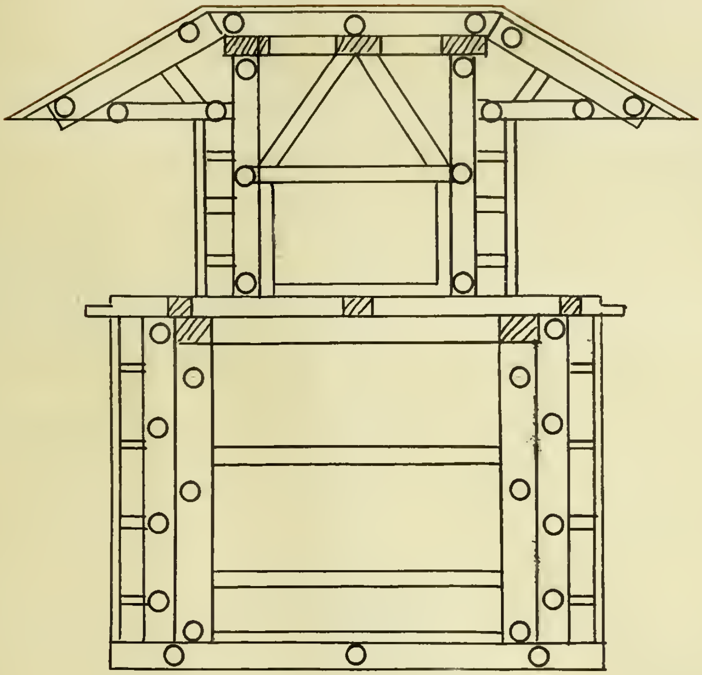

Fig 4

Austrian System of Timbering

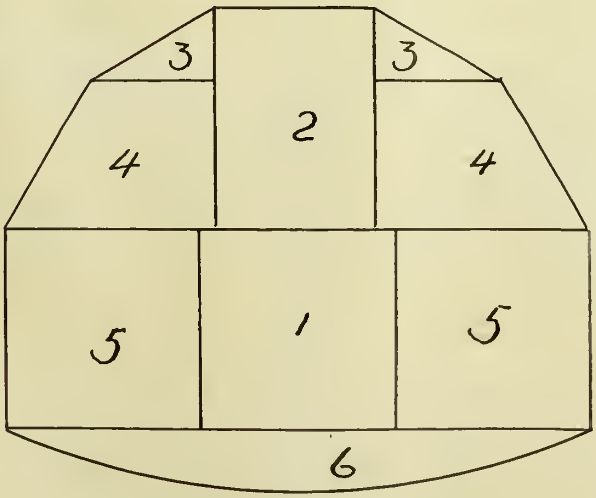

Fig 4a

Sequence of Excavation

The plan of propping which results from the core system tends to concentrate the pressure at one point and this is, of course, objectionable. The timbering in this system should be arranged so that heavy pressure on all sides will tend to press and bend it together, and not to press it at one point and loosen it at another. When there is a heavy wet core it will tend to sink at the top and to bulge out at the sides, thus allowing the roof timbers to loosen and sink also.

The main characteristic of the Austrian system is its great strength afforded by the arrangement of the timber. It is stronger than any of the other systems and the chief reason for its strength lies in the fact that no large spaces except the middle are left unsupported. Fig. 4 shows the method of timbering and Fig. 4a gives the sequence of operation. To finish excavating the section shown in Fig. 4, it would be enlarged down the sides and the timbering supporting the roof would be braced against the vertical timbers shown. A good point to emphasize in regard to the strength of this system is the excellent provision for cross-wise and longitudinal connections of sets. Then again, it is easily seen that there is no concentration of pressure at any one point as often happens to be the case with center core propping, but in this case the pressure is distributed through and held by all the timbers. The question which often arises, Is not this system too strong? There is no doubt that in most soft ground work the English system is amply strong, and, when it can be used, it will, without doubt, furnish the most ready and cheap work. The Austrian system also has the advantage of a bottom heading, thereby securing early, good drainage and ventilation. The facilities

for transportation are good, but the freedom of the work is not so great owing to the timber in the way, and, therefore, the masonary is apt to cost more than with the English system.

As these systems are all in use in Europe and the relative merits of each have caused much discussion, and as they are very much apart from our system, it is deemed advisable to give a general comparison of the four leading European systems before describing the American system.

In Europe, these four systems just described, are in constant use and none lack for friends to proclaim their merits, but when Rziha says that the Austrian is the best for any and all circumstances, we think that he has allowed his prejudice to blind his judgment. We would not think of using it in many of our tunnels in this country which penetrate slates and shales. It would be a wanton waste of timber and time. Then, again, the English system has a large number of good points, giving, as it does, cheap excavation, with free, open space for the masons and plenty of strength for ninety per cent of the ground which is likely to be encountered. So that, in spite of Rziha's sweeping statement, the English system will, doubtless, meet, in the future, with great favor in building tunnels through ordinary soft ground.

In soft ground, the German center core system has been well and sufficiently tried under all conditions, and the verdict of the foreign engineers is decidedly against it. Its record in soft ground leaves nothing that can be said in its favor.

As to the Belgian system, it would seem to be condemned for general use in soft ground as the underpinning of the arch in this material involves too much danger; but as to its application

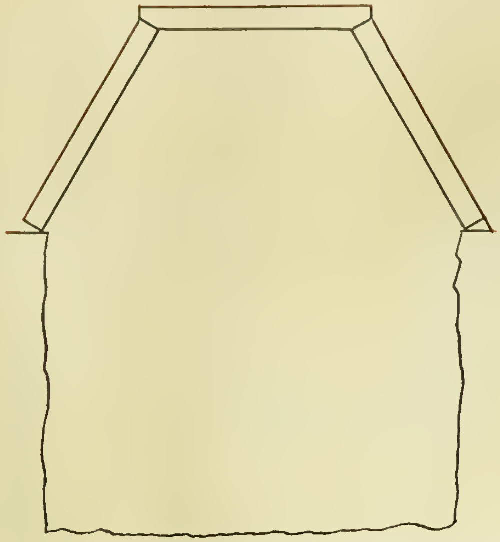

Fig 5

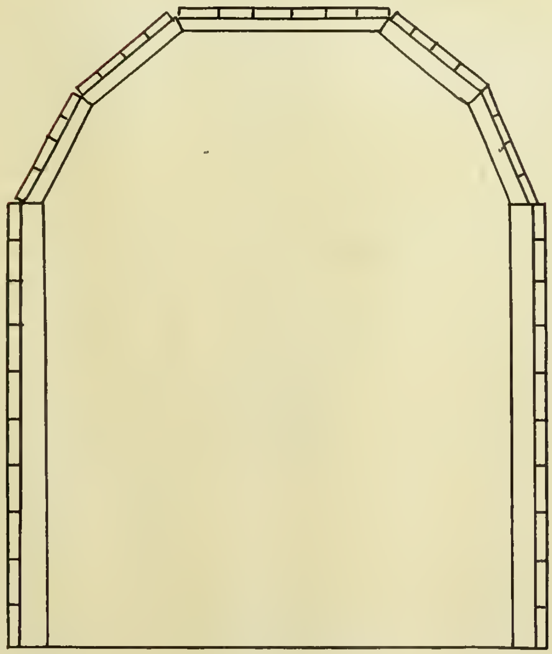

Fig 5a

American Methods of Timbering

in moderately hard ground, it seems to be a favorite system abroad and established as far as the future is concerned.

It would seem impossible as well as unfair to try and decide the best system for all work. Conditions are so varied that the system to be used in any case should and does rest in the hands of the engineer in charge.

The American tunnel timbering, as a system, has not been universally recognized as such, nor is it generally known, especially in Europe, that we have here as distinct and marked a national system, as any of the European systems can be said to be distinct. Our system is absolutely unlike any other system in that, owing to the great amount of timber present when most of our tunnels were built, it has become a permanent system of timbering. It might well come under lining, but a permanent system of timbering seems to classify it better than could be done under "Linings".

This system of permanent timbering is used in the United States in three forms. 1st. In the common form of an ordinary rafter truss, as shown in Fig. 5, as shown, the lagging is supported by horizontal rafters, perpendicular to the axis of the tunnel, which are, in turn, supported by the two inclined struts which rest upon the posts.

2nd. As block arching, as shown in Fig. 5a. In this, the arching, which supports the lagging, may be made up of five to nine segments. The method of jointing and support on the posts is shown by the sketch.

3rd. As heavy permanent centers, as shown in Fig. 5b. These centers which support the lagging, are made of heavy plank segments and are bolted together.

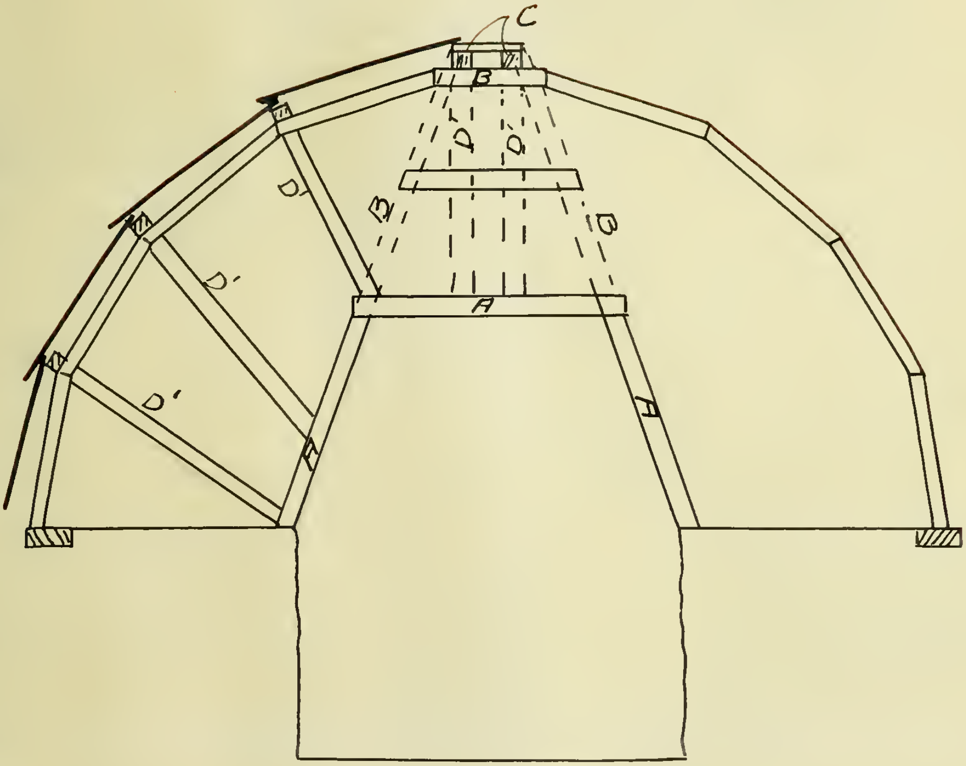

Fig 6

Timbering Used in the St. Clair Tunnel

The ordinary rafter truss is not strictly native to Americans, although we added the permanent feature of its use, but the block arching system is strictly a typical American system and is in general use here. It, though appearing fragile, has been very successful and when it has failed, it has been in extremely heavy soft soil, in consequence of exceptional circumstances.

SOME SPECIFIC EXAMPLES OF TUNNEL TIMBERING.

(The St. Clair Tunnel.) The St. Clair tunnel, on the Schuylkill Valley branch of the Penn. R.R., near Pottsville, was first projected for a single track tunnel, and driven on that basis for almost its entire length of 800 feet. The material penetrated was the usual coal formation of that region, made up of slate, shale, loose rock and coal. The single track tunnel was driven and timbered with 12"x12" sticks as shown at $A_i A_i^{A}$ in Fig. 6. Owing to the increase of traffic, it was decided to enlarge the tunnel so as to accomodate a double track railroad, and the work was carried out substantially, as follows: The widening operations were begun by driving the top heading (about 6'x6') as shown by $B_j B_i B$ and timbering with 12"x12" sticks, resting upon and continuing the lines of the original set. The longitudinal timbers C-C were next put in place, and temporarily propped from the cap A by means of D'-D'. This being done, the heading was widened towards each branch equally, and the side posts B-B removed. As the widening progressed, 8"x8"x16' long, longitudinal sticks were put in and cornered by poling boards, following the intended curve of the double track tunnel. These were braced from the single track sets by props D'D', both sides being carried out evenly to prevent shoving. This system was carried out until the

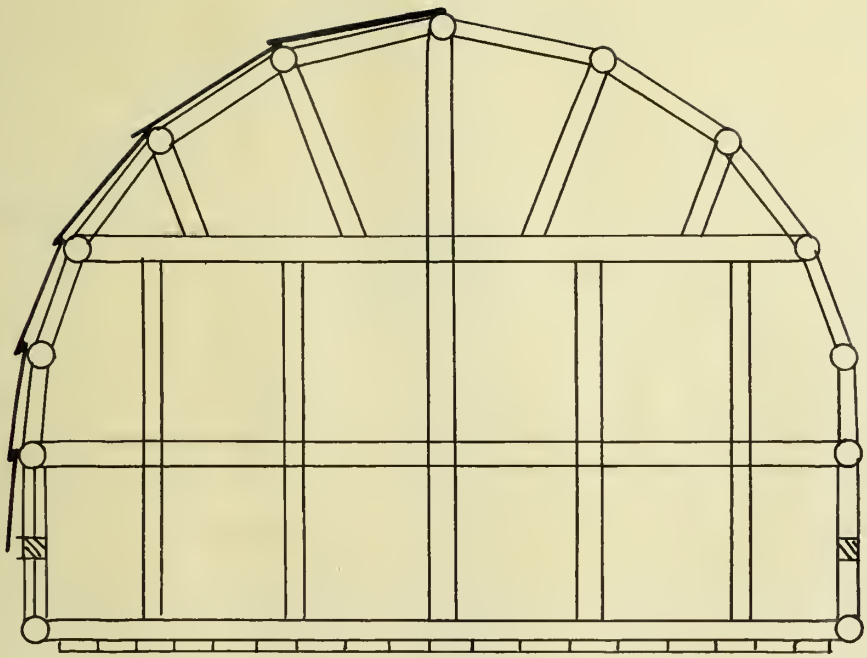

Fig 7

Timbebering Used in New Croton Aqueduct

springing line was reached. A 8"x12"x12' wall plate was then put in. Upon this was started the framed timber arch, made up of segments of 12"x12' pieces, each about 4' 3" long, with joints cut on radial lines. When this arch was keyed in, the props were removed which held the longitudinal stringers. The twelve foot wall plate carried four of these ribs and the only sheeting required was that used in enlarging the tunnel originally. When the arch ribs were in place for one 12' section, the timbering of the single track tunnel was removed and the tunnel widened below the springing line.

(New Crotan Aqueduct). In the tunnel work in the New Crotan Aqueduct, the rock suddenly ended, and in spite of all efforts made to stop it, a large inflow of wet sand and gravel took place, which completely filled the heading, forming a wedge shape heading extending back for a considerable distance.

In boring through this loose material a much larger section was excavated than necessary, and the masonry built inside of this.

The method of operation was, as follows: Extending a little above and in line with the crown of the masonry was a drift about three feet high and nine feet wide. When beginning a section, an opening is made at the top of the heading large enough to admit a square stick about 10"x10", equal in length to the width of the drift. This timber is supported at its ends and center by vertical posts, as shown in Fig. 7. On top of this timber are driven poling boards or strips about four feet long. The back ends rest upon this timber and they are driven at such an angle that the front ends will rest upon the next timber put in. The sides of this drift are protected in the same way. This operation is re-

peated until a section ten or twelve feet long is excavated, when it is provided with plank sheathing.

The crown center bar is now pulled forward, if possible, and if not, a new one was put in. If it cost more than $3.00 to pull a bar, it was left in place by the contractors. The bar is pulled forward until its forward end rests upon the heading of the drift and its rear end was on the completed masonry. The forward end was slightly elevated so that when the section was completed, it could be dropped in order to free it from the earth and admit of its being drawn forward to the next section. The two side bars are then pulled forward (when possible) and are braced to the center one. With this as a foundation, the sides are extended down to a point below the invert of the tunnel.

Nearly horizontal strips are driven from the top of the side crown bars and other bars are inserted under their ends. From these latter bars, other strips are driven and bars placed in position. The inclination of the poling strips increases from the crown until, at the sides, they are nearly vertical. Each bar is braced from the two beside it. The chamber is excavated and the sides are carried downward. The floor was covered with both a longitudinal and transverse course of planking. The gravel was coarse so that a packet must be formed for each poling strip. The intense weight above prevented any attempt being made to pull any bars other than the three crown bars. Hay was found to be the best cheap material for calking. The work was extremely slow and tedious, only averaging about one foot per day.

(Betchworth Tunnel). In the Betchworth tunnel at Darking,

Fig 8

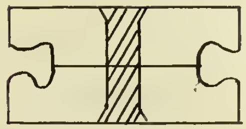

Fig 8a

Crown Bar Needles

England, a portion of the tunnel caved in. The caving material consisted of loose, dry sand. About one hundred and seventy-five feet of the tunnel was filled. In repairing the break, a system of vertical poling boards were used in excavating the dry sand. The boards used were 2" thick by 3' long. Work was started at the crown, and the sand thrown back on slope and the boards pushed forward and then another set introduced below and so on to the bottom. An immense amount of timber was used and cost was $7.25. per linear yard.

(The King's CrossStation Tunnel). In the King's Cross Station of the Great Northern Railroad in London was first used the iron needle crown bar system of timbering. The introduction of this system of timbering was imperative, owing to the lack of room for the heavy timbers which would have been required. Fig. 8 shows the design of the first bars used, and Fig. 8a shows a later improved design. As may be seen, these iron or steel needles are grooved longitudinally. They may be linked together and have sufficient play to allow of an arched form being readily obtained but, at the same time, only longitudinal motion is possible.

In Fig. 8c, the double needle was first designed as one piece, but it couldn't be rolled successfully, so it was made of two single needles, inverted, with counter sunk rivets, as shown.

These needles joined together, form a temporary roofing, and at the beginning of the work, may be supported on timbers at each end while the masonry is being put underneath. The needles used in this tunnel were 10' long 6" wide and 2" thick. After the completion of the brick-work, the needles were pushed forward in triplets.

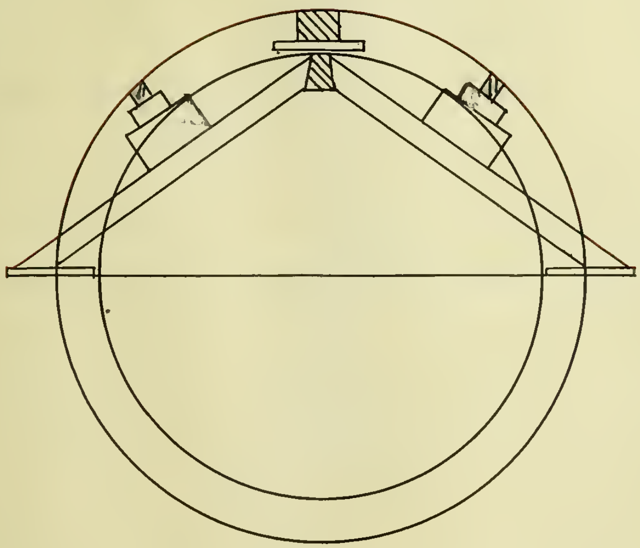

Fig 10

Crutch System of Timbering

In this system the excavation is reduced to a minimum and the needles may be made to fit any section, but the main advantage gained is in head room.

West Va. & Pitt.R.R. Tunnel.- In the construction of a short tunnel on the W. Va. & Pitts. R.R., is illustrated a very common practice among American engineers of lining the tunnel with timber and not substituting masonry until the timber was no longer safe. The road could not afford the masonry at the time of building the tunnel so the permanent segmented arch system (Fig. 5_b) of timbering wasadopted. Provision was made for relining by making the cross section large enough for the lining to be constructed inside of the tinbering.

The timber arches were made up of 12" x 12" sticks and were simply laid on segmental arch centers. The centers were made in two pieces bolted together at the top and then blacked up at the bottom to the proper height.

Crutch System.- Fig. 10 shows a sketch of the crutch system of timbering as it is called. It is hardly of enough importance to be classified as a separate system, but as it is used to quite an extent in tunnels of small cross section such as tunnels for sewers it is worth noticing. As shown, the horizontal plates are set in the sides of the excavation at about the level of the center of the tunnel and upon these plates rest the inverted Vs as shown. The apex supports a longitudon--al cross timber. Upon the outside of these V-shape crutch timbers blocking is placed to support the longitudonal timbers that in turn support the sides of the excavation. The number of these timbers will vary with the character of the ground

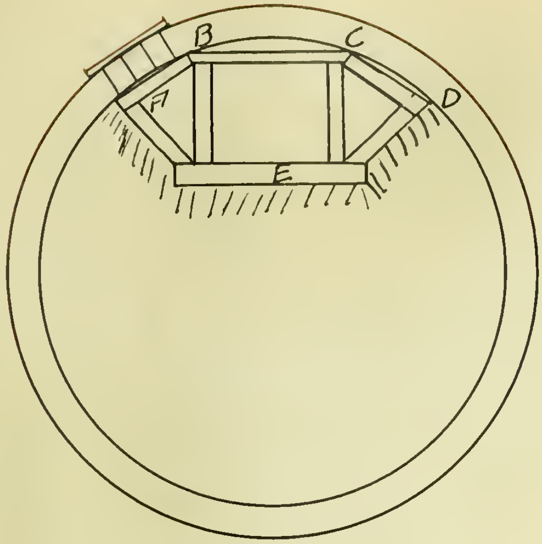

Fig 11

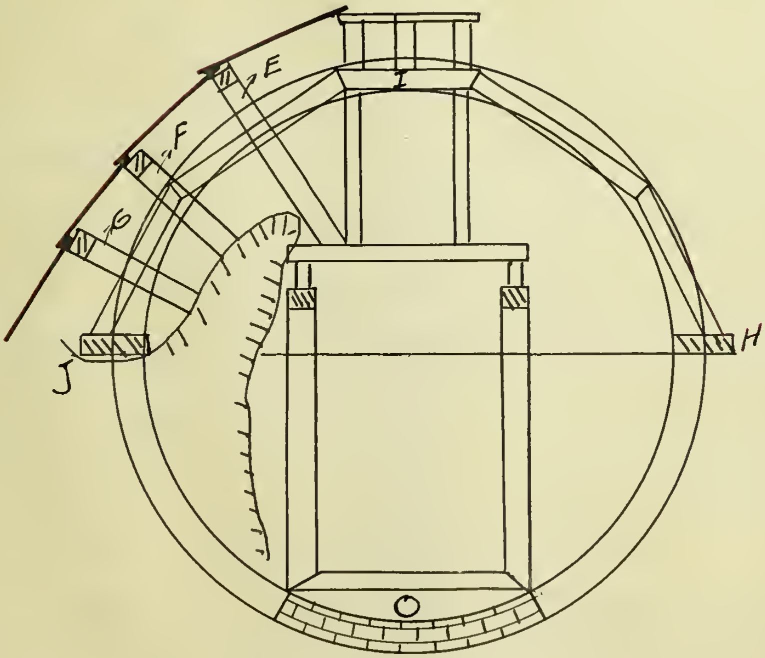

Fig 11a

Timbering with Meem's Poling Boards and Details of Construction

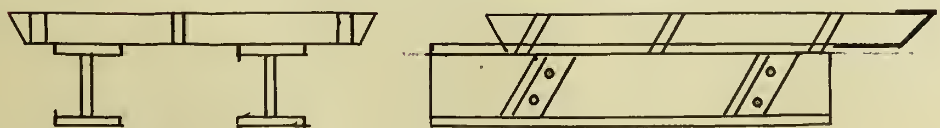

Fig 11b

which is penetrated.

The rear ends of these longitudional bars are carried by the masonry and the front ends by posts at the face and the centers are of course supported by the crutches. All the timbers in this system are set by wedges.

Meem Poling Board.- In the construction of the 64th St. Sewer Tunnel and outlet sewer at Brooklyn was first introduced the Meem Poling Board method of timbering.

In this method the first work is to take out a top heading embracing about a quarter of the perimeter of the section. The first step in doing this is to erect the segmental guide A, B, C, D, E (Fig. 11). Over the top of these frames was slipped the ends of five poling boards constructed as shown in Fig. 11b. These poling boards are gradually pushed ahead into the soil and the excavation is carried on under their cover. After the poling boards have been pushed ahead a little distance another guide frame is erected ahead of the first and as the excavation proceeds still a third guide frame is inserted. The five poling boards are finally being carried by five guide frames when the work has been fully started.

The next step is to carry the excavation down on each side, following the perimeter of the section as shown in Fig. 11a. During this operation the roof was braced by E, F, G, etc., which support lagging boards. As soon as the side cuts were completed the segmental frame timbering H, J and K shown in Fig.11a was erected and struts were inserted between its top and the roof lagging to relieve the poling boards and the previous timbering. The excavation was then carried down along the

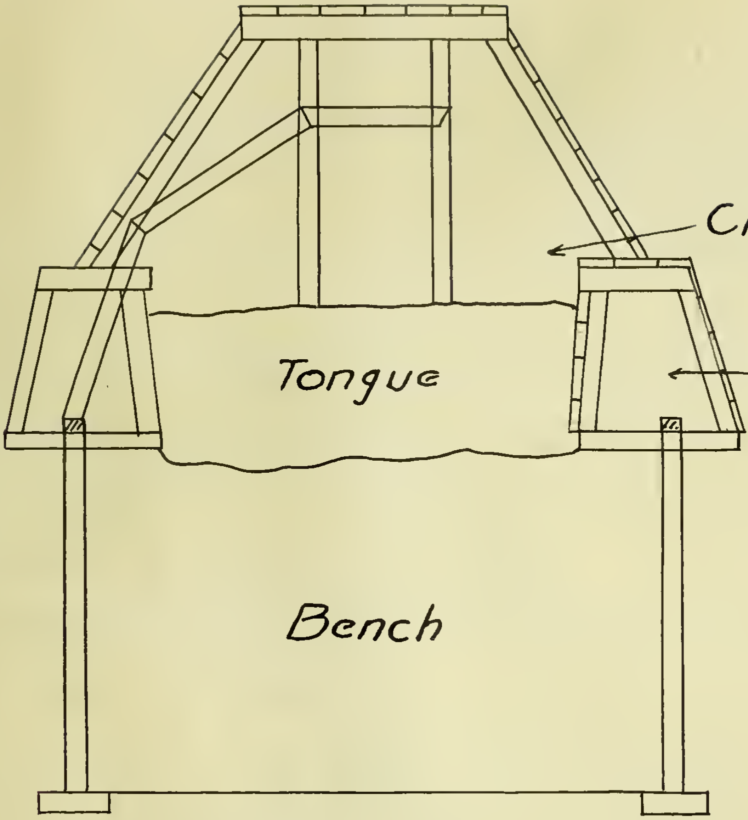

Fig 12

Timbering in Dry Gravel at Michel Creek Loop

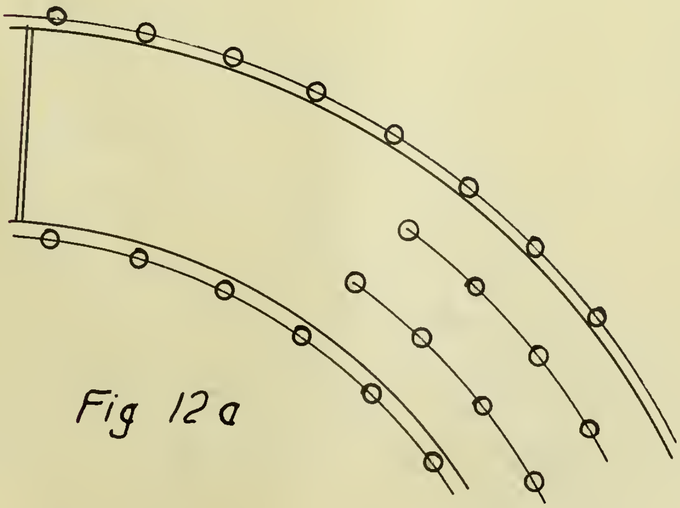

Fig 12 a

Diagram Plan

perimeter of the section using radial bracing and lagging to carry the side of the excavation until the section had been opened sufficiently to permit the construction of a portion of the brick work invert. The timbering L, M, N, O was then erected on this masonry to carry the segmental frame. The excavation was now ready for the masonry lining which will be discussed under that head.

Michel Creek Loop Tunnel.- The tunnel through loose gravel at a point known as Michel Creek Loop on the Crow's Nest Pass Line of the Canadian Pacific was attended by some considerable difficulties and the timbering is unique.

Figure 12 shows a cross sectional view of the timbering and Figure 12a shows a diagram plan.

The excavation was started by driving two side drifts into the upper face, 8' high and 6' wide leaving about 8' of earth between them. When these drifts had advanced about 20' a wall plate was set in the outer side of each and securely locked in place. A crown drift extending from the level of the top of the side drifts and about 4' above connected the two and allowed the 12' x 12' timber arch to be erected.

The details of timbering these side drifts is interesting . First a frame of 8" round timbers was prepared as shown in Figure 12 . The sill was set accurately to the elevation of the under side of the wall plate. The post of these side drift frames were about 8' long and the outer one was battered more than the inner one. The drift frame being set up, the face in front was walled up with 1" breast-boards braced with inclined struts. All around the outside of the frame close lagging was

now entered and driven forward into the face by sledges. 2" x 4" x 5'long was the size used. Each piece was first driven about half way with an outward and upward lead so as to form a close horizontal joint and also to permit of entering the next set of lagging at the next drift as the pressure was too great to admit of forcing the next set between the post and the set in place. In this way a hood of horizontal sheet piling was secured for over 2' in advance of the breast boarding.

The breast boards were now removed one at a time and pushed forward, beginning at the top, to the limit of the hood. A false frame was set up back of the new position of the breast wall. The lagging was then driven in its full length and the breast wall advanced as before and a second frame put in. These frames were about 4' apart. The lagging was blocked to hold it away from the forward frame and in this way the other lagging could be started without difficulty. The outward plan of the lagging left about 4" to be blocked in. The crown drift was driven in a similar manner. Over fifty pieces of lagging were required to sheet around each drift frame and as each piece drove hard, the progress was very slow.

The posts were set under the wall plates in an inclined position and jacked out at the bottom until they were plumb.

The bottom drift was kept breast-boarded at each side but the central part was allowed to slope.

TUNNEL LINING

In almost every tunnel at least a part of the length must be lined. No matter what the lining material is to be, a form or center upon which the masonry is to be constructed must first be built.

A good tunnel centering should fulfill certain conditions if it is to allow of the most successful prosedution of the work. 1st.- It must have a large opening so as to allow unencumbered work. 2nd.- It should be easy and simple to set up and take down, and this requires that the different parts be not too large or heavy. 3rd.- They should be arranged so that platforms and scaffolds for the masons can be readily attached to them. In constructing tunnel centers it must beremembered that the center is carrying not only the weight of the lining but in many cases the weight of the ground as well, and the construction should be such that it will admit of rapid strengthening whenever necessary. And while the centers must needs be strong they should be carefully proportioned and have no extra material in them.

In building centers as in tunneling the longitudional connection of centers does not require much bracing as the sheeting plank affords this as the arch goes up and the pressure increases. The support of the centers will depend upon the nature of the ground but it is always good policy to see that the

footing of the centers does not have any connection with the tunnel-timbering.

Tunnel masonry may be divided into four divisions, viz: foundation, invert, side-walls and arch.

While the foundation for the side walls of a tunnel is not as important as the foundation of a sky scraper, still it is necessary that something be put in to support the side walls. The depth of this foundation course varies with the material penetrated.

When the English System of timbering, which distributes the pressure around the circumference of the tunnel, is used, and where free open space is early provided the invert is generally built first. In some cases where the upward pressure is very great it is necessary to provide some sort of bracing to hold the invert down in place until the cement hardens and the abutments are in place. It is not always necessary for the invert to be built and in soils which will permit the side walls are carried down to the foundation and the invert omitted. If it is afterwards deemed advisable to put in the invert it can be done with but little difficulty. The side walls are very generally laid up to the springing line with horizontal mortor joints and the arch carried on from there with radial mortan joints. Tunnel masonry does not require the same care as in open air, as to appearances, but the fact that it must develop great strength makes it important that the work should be carefully done. A good fit at the joints should be insisted upon and the spauling of the joints should be forbidden.

A sufficient number of headers should be used according to

the pressure of the ground, and the joints should be carefully broken.

In most systems of tunneling the side walls are constructed first and the arch afterwards, but in the Belgian System the arch is constructed first, then underpinned and the excavation completed and the side walls built. The German System is something like the Belgian in this respect. The arch centers rest on the central core and the side walls and the arch are under construction at the same time.

The leading materials used intunnel linings are brick, stone, concrete, iron and timber. The use of the latter as a material for lining seemed to fit better under timbering and it was so considered there.

Brick has always been a favorite material for tunnel masonry. They are very well adapted to the peculiar needs of tunnel linings. They can be obtained almost anywhere and in many tunnels have been made on the ground from the material taken from the tunnel. They are readily adjusted to any form of cross section. They come in small units and are easily handled. By the use of successive courses an arch of any desired thickness can be obtained. In the past few years concrete is being used to some extent where brick would have formerly been used, but still brick is used as a material for tunnel lining more than any other and seems likely to hold the place of honor indefinitely. The greatest objection to concrete especially in the arch construction is the inability, owing to lack of room, to get it properly tamped. Then again, the extra work and expense required to build the forms tends to limit its use. Stone has

been used a great deal for building arches and in very heavy ground developes more strength than the brick lining. The stone lining as a rule is expensive. It comes to the work in large units which are hard and inconvenient to handle. Then the dressing of the stone to radial lines is expensive. But in many soils the pressure is so great that the stone lining is necessary.

Iron as a lining has never come into general use. It has been used in a few pieces of sub-aqueous, where a cast iron tube would be surrounded by a thick layer of concrete.

It would be foolish to say which material will give the best results for any and all kinds of work, but as a general rule for tunnels, through ordinary or only fairly soft soils, brick will generally be found to give a very efficient and economical lining. Where the pressure is excessive it may be necessary to use stone masonry and other conditions may arise which would give the preference to concrete or iron lining, all depending upon the local conditions and upon the judgment of the engineer in charge

SOME EXAMPLES OF LININGS

The Baltimore Belt Tunnel.- This tunnel was built as a subway, part of it in open cut but the most of it was built as a tunnel. It is not different in most respects from ordinary tunnel practice in dealing with the water bearing material. There were, however, one or two features of construction which are worthy of notice. The building of the invert was one of these. When the ground was sufficiently stable a shallow coffer-dam of from 2' to 10' and the full width of the tunnel was formed of sheet piling. The material was excavated and the invert of 8" of concrete was made. In less stable material this coffer-dam would be divided transversely into three coffer-dams. In the latter case the masonry of the middle section was built and the side sections afterwards. In ground which was still more unstable a flooring of 1 1/4" plank was laid down in the coffer-dam and held in place by struts resting against the transverse timbers of the coffer-dam.

At one place the pressure of the water was so great that it washed in the earth in spite of the packing of hay and cement above the timbering. At this point a number of perforated pipes were driven into the soil and cement grout was forced through them solidifying the soil and stopping thewater. The area of radius of penetration of the cement from the pipes was about 10'.

Mullan Tunnel. N.P. Ry.- The original lining was of timber.

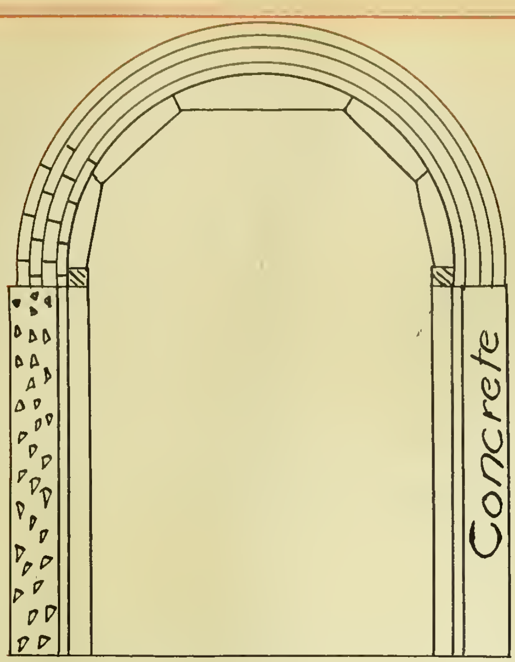

Fig 13

Old Timbering and Masonry Lining in Mullan Tunnel N.P.Ry.

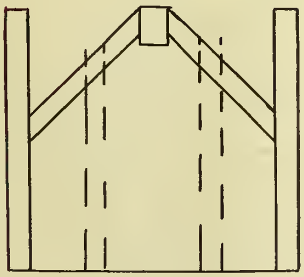

Fig 13b

consisting of sets spaced 4' apart with 12" x 12" posts supporting wall plates and a 5 segment arch of 12" x 12" timbers as shown in Figure 13. The arch was covered with 4" lagging and the open space between that and the roof packed with cord-wood. The clear width was 16' and the clear height was 20' except in places where it was reduced by new timbering inside of the original. Figure 13 shows the masonry lining which was adopted.

In removing the old timbering, a seven foot section would be taken out by removing one post and supporting the roof by slanting struts fastened to the other posts as shown in Figure 13b. After the backing was cleared away two posts were set up and lagging built up for the forms for the concrete side walls. Several of these seven foot sections were prepared at the same time, each being separated by 5 feet of the old timbering. A morter car was then run along and enough 1:3 mortar was run into each section to make an 8" layer of concrete. When the car moved on to the next section enough crushed stone was shoveled into the mortar. The walls were thus built up in 8" layers and became hard enough to support the arches in from ten to fourteen days. The arches were then allowed to rest on the concrete and the rest of the old timbering was taken out and the walls built up as before. An average progress of about 30' of side wall per day was made.

The centering for the brick arch is as shown in Figure 13. From 3' to 9' feet of arch was removed at a time depending upon the nature of the ground. To remove the old timber arch one of the segments was partially sawed in two and a small charge of giant powder was exploded in it, and the resulting debris,

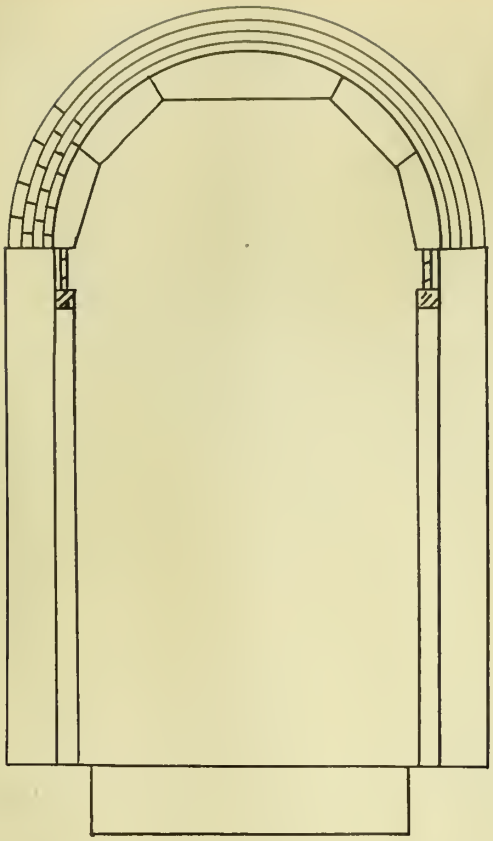

Fig 14

Old Timbering and Masonry Lining on Norfolk and Western Ry. Tunnel showing movable centers

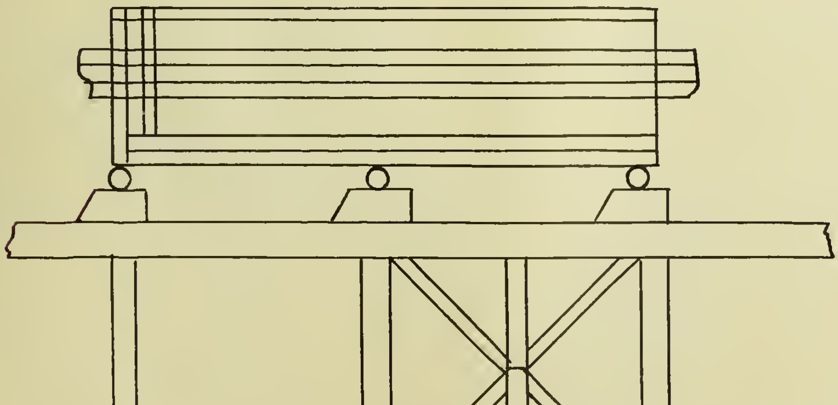

Fig 14a

Longitudinal Section

cord wood, rock, etc. being caught on a platform extending under the section. The centers were then set and the 20" arch consisting of four rings of brick was begun, the cement car being used as a place for mixing the mortar.

Norfolk & Western Railway Tunnel. This tunnel is 1902 feet long, but only 1410 feet was lined with timber, necessitating relining with brick masonry. The old timber lining consisted of bents space three feet apart. The tunnel was through rock, but much of it was seamy and disintegrated upon exposure to the air. Breaks in the roof from 1' to 12' made it necessary that only a small portion of the timber lining be removed at the time and that the brick arch be built as quickly as possible. Also that all details of the centering, etc. should be so arranged as to allow the uninterrupted passage of trains.

As shown in Fig. 14, two side trussles were used to carry the adjustable centering for the roof arch. Two sections of these trussles were used alternately, one being carried forward to remove the timbering while the masons were using the other. As shown in Fig. 14a, set-screws were used to bring the lagging up to the proper heighth. A progress of about 2' or 3' of lining complete, was made per day.

COSTS.

The cost data of tunnel timbering are very meager, and what was obtained that was of any value, was inserted in with the descriptions of the work.

With regard to the lining of tunnels, more cost data has been available and a short table of costs per linear foot of a number of tunnels will be given. The table is only intended to show the wide range of values due to different conditions.

Name or location of tunnel.	Cost of lining per linear foot.
Norfolk & Western Ry.,	$33.50
R. P. Ry.,-Mullan,	50.00
Carr's Penn. Ry.,	65.20
B. & O. Ry.- Greenfield Bridge,	12.60
Boston & Albany-Canaan,	9.60
B. & O. Ry.-Doe Gully,	31.10
Allegheny Valley- Anthony's Neck,	32.15
C. & O. Ry.,-Lewis,	21.10
Albany & Susquehanna-Webster,	24.80
B. & O. Ry.-Murray's,	26.20

While abundant cost data on linings are available, it has been very hard to find any information on the cost per linear foot.